2 The natural sciences

> **The progress of science is strewn, like an ancient desert trail, with the bleached skeletons of discarded theories which once seemed to possess eternal life.**
> *Arthur Koestler*

> The notion of absolute truth is shown to be in poor correspondence with the actual development of science. Scientific truths are better regarded as relationships holding in some limited domain.
> *David Bohm*

> IN QUESTIONS OF SCIENCE THE AUTHORITY OF A THOUSAND IS NOT WORTH THE HUMBLE REASONING OF A SINGLE INDIVIDUAL.
> *Galileo Galilei*

> Science is built with facts just as a house is built with bricks, but a collection of facts cannot be called a science any more than a pile of bricks can be called a house.
> *Henri Poincaré*

> SCIENCE DOES NOT GIVE US THE TASTE OF THE SOUP.
> *Albert Einstein*

> In science the primary duty of ideas is to be useful and interesting; even more than 'true'.
> *Wilfred Trotter*

> *When a distinguished but elderly scientist states that something is possible, he is almost always right. When he states that something is impossible, he is very probably wrong.*
> *Arthur C. Clarke*

> The most incomprehensible thing about the world is that it is comprehensible.
> *Albert Einstein*

> Far more marvellous is the truth than any artists of the past imagined! What men are poets who can speak of Jupiter as a man, but if he is an immense spinning sphere of methane and ammonia must be silent?
> *Richard Feynman*

> Everything you've learned in school as 'obvious' becomes less and less obvious as you begin to study the Universe. For example, there are no solids in the Universe. There's not even a suggestion of a solid. There are no absolute continuums. There are no surfaces. There are no straight lines.
> *R. Buckminster Fuller*

> All science is either physics or stamp collecting.
> *Ernest Rutherford*

Aims

By the end of this chapter you should:

- **understand what elements are often said to make up the classical scientific method (with examples, preferably some of your own)**
- **recognise the limits and problems of the classical scientific method and appreciate that the growth of scientific knowledge is a complex phenomenon that cannot be rigidly defined**
- **know what makes a claim a scientific claim and the meaning of the term 'pseudo-science'**
- **appreciate the meaning of 'truth' in a scientific context**
- **be able to discuss the interplay between science and other areas, such as the arts and religion**
- **appreciate that the scientific way of thinking may have important consequences for our beliefs in other areas.**

Introduction

The natural sciences are one of humankind's great achievements. In popular culture to hear that something is 'scientifically proven' is almost the same thing as hearing that it is 'definitely true' and science has certainly achieved many wonderful, and terrible, advances in recent history. In a search for reliable knowledge, science must rank high on any list. After all, we trust scientific beliefs with our lives every time we get in a car or aeroplane, use a lift or eat processed foods. So what is it about the natural sciences that make them so special?

There are few people who answer this question as well as Richard Feynman, a visionary physicist who fundamentally changed our understanding of nature. He wrote:

> *The things with which we concern ourselves in science appear in a myriad of forms, and with a multitude of attributes. For example, if we stand on the shore and look at the sea, we see the water, the waves breaking, the foam, the sloshing motion of the water, the sound, the air, the winds and the clouds, the sun and the blue sky, and light; there is sand and there are rocks of various hardness and permanence, colour and texture. There are animals and seaweed, hunger and disease, and the observer on the beach; there may be even happiness and thought. Any other spot in nature has a similar variety of things and influences. It is always as complicated as that, no matter where it is. Curiosity demands that we ask questions, that we try to put things together and try to understand this multitude of aspects as perhaps resulting from the action of a relatively small number of elemental things and forces acting in an infinite variety of combinations.*
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> *For example: Is the sand other than the rocks? That is, is the sand perhaps nothing but a great number of very tiny stones? Is the moon a great rock? If we understood rocks, would we also understand the sand and the moon? Is the wind a sloshing of the air analogous to the sloshing motion of the water in the sea? What common features do different movements have? What is common to different kinds of sound? How many different colours are there? And so on. In this way we try*

gradually to analyse all things, to put together things which at first sight look different, with the hope that we may be able to reduce the number of different things and thereby understand them better.

A few hundred years ago, a method was devised to find partial answers to such questions. Observation, reason, and experiment make up what we call the scientific method.

What do we mean by 'understanding' something? We can imagine that this complicated array of moving things which constitutes 'the world' is something like a great chess game being played by the gods, and we are observers of the game. We do not know what the rules of the game are; all we are allowed to do is to watch the playing. Of course, if we watch long enough, we may eventually catch on to a few of the rules. Knowing the rules of the game is what we mean by 'understanding'. Even if we knew every rule, however, we might not be able to understand why a particular move is made in the game, merely because it is too complicated and our minds are limited. If you play chess you must know that it is easy to learn all the rules, and yet it is often very hard to select the best move or to understand why a player moves as he does. So it is in nature, only much more so; but we may be able at least to find all the rules. Actually, we do not have all the rules now. (Every once in a while something like castling is going on that we still do not understand.) Aside from not knowing all of the rules, what we really can explain in terms of those rules is very limited, because almost all situations are so enormously complicated that we cannot follow the play of the game using the rules, much less tell what is going to happen next. We must, therefore, limit ourselves to the more basic question of the rules of the game. If we know the rules, we consider that we 'understand' the world.

You find here, in a nutshell, what many scientists believe science to be. You may be surprised to hear them wax lyrical about curiosity, awe, beauty, rigour, honesty and humility – but contrary to some stereotypes science can inspire lofty emotion! This isn't that surprising – it is, after all, a human endeavour.

Occasionally, you hear science spoken of in an arrogant fashion, with disdain for 'non-scientific' thoughts or processes, but this usually says more about the speaker than about science. Feynman again:

We must, incidentally, make it clear from the beginning that if a thing is not a science, it is not necessarily bad. For example, love is not a science. So, if something is said not to be a science, it does not mean that there is something wrong with it; it just means that it is not a science.

A Explain the game analogy that Feynman uses to explain the aims of science.
B Do you think the analogy is a good one? Explain your answer.
C How does this fit in with your science lessons at school?

The 'scientific method'

Let us look now, in some more detail, at what makes science so special. As Feynman says, **observation**, **reason** and **experiment** make up what we call the **scientific method**. It is also very important that the observations, reasoning and

We found that the theory did not fit the facts; and we were delighted, because this is how science advances.

O. R. Frisch

experiments can be *repeated and checked independently* by other observers. If you and your friends are the only ones to have seen or understood something, then it doesn't count as science.

Your sighting of a UFO last year is not likely to be accepted by scientists. If the UFO had really been there, radar equipment would have picked it up, and it would have been reported. Your report has not received independent experimental confirmation where there should have been, so your claim is not scientific. That is not to say that it is definitely false, just that it is highly likely to be false. (Of course, it may be that UFOs have the ability to hide from radar; we cannot rule this out – when we have so-called Stealth technology it hardly seems impossible to believe that visiting extra-terrestrials also have it. However, the point stands – we must look to the evidence and evaluate it. Most scientists believe that the evidence is unconvincing, and that the best explanations do not involve aliens.)

We will say a little bit more about experimental confirmation later on, but here we return to Feynman to talk about one other key element of science, namely **imagination**.

But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment itself helps to produce these laws, in the sense that it gives us hints. But also needed is imagination to create from these hints the great generalisations – to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess.

We can examine these ideas with reference to the following two simple claims:

1 The Earth is flat.
2 The Earth is round.

Were these scientific claims at the time they were made? Let us first turn to claim **1**.

At the time, it was certainly observed that the Earth was flat. We are not talking about there being a few mountains here and there, but the fact that, on the whole, the Earth seemed flat. People certainly did their reasoning: things on a slope have a tendency to slide down the slope, so if the Earth weren't flat, people would start sliding at some stage. But this is not what happens. So at this stage, thinking that the Earth was flat was a reasonable scientific belief. Here we have the first indication that science and truth are not necessarily intimately related.

But what about testing claim **1**? People did that, too. They travelled over land and over sea. Some went to look for the edge of the planet, since there should be one assuming the Earth has finite size. The fact that they did not find an edge helped a great deal in the eventual rejection of claim **1**.

Now let's look at claim **2**. Here one clearly needed some imagination. At the time, there was no direct observation available. But there were hints: perhaps the moon is not a disc painted on the sky but a solid sphere a long way off; perhaps our Earth is similar to it. Also, no edge to the Earth was ever found, and on the contrary, there were strange reports of sightings of

similar land found by sailing east and sailing west. So someone used some imagination and made a bold move: suppose that the Earth is round.

Now what? We need to test this claim experimentally. How do we do that without aeroplanes and satellites? We reason and think of possible consequences, and then test those consequences. One immediate consequence of a round Earth is that there should be a horizon. If boats disappear over the horizon, their mast should disappear last. Also, we should be able to see further the higher up we go.

These consequences were known to be correct experimentally. After all, boats always had somebody high up in the mast, so that they could look further. These consequences could not be explained in a straightforward manner with claim **1**. The first seed of doubt was sown. The distance to the horizon is easy to measure experimentally: all it takes is you, a friend and a small boat. It turns out to be about 5 km if your eyes are 2 m above sea level. Now we can use some mathematics and lo and behold, we find the size of the Earth! The radius should be about 6,000 km.

So by simply applying reason, we see that claim **2** implies precise limitations on the size of our planet! If it is round, then its radius had better be 6,000 km, or, equivalently, its circumference should be about 40,000 km. Could this claim be tested experimentally? Well, it could certainly have proved false. That is, it could have been **falsified**. If people had been able to sail 50,000 km west without returning to the start, claim **2** would have been in trouble. But the fact of the matter was that the 40,000 km circumference tallied quite well with the earlier suspicions of having reached the same land from two different directions. Of course, it could be that the Earth isn't a sphere but an egg shape, and that the voyages which seemed to confirm a circumference of 40,000 km were only good for one particular direction. On the basis of theory and evidence so far discussed, we can't be sure.

This is the essence of scientific truth: it can never be proved experimentally that a claim is correct, but it can be proved that it's wrong (in which case it is said that the theory has been falsified). This might seem a little strange because it is easy to assume that scientific laws have been proven but, in fact, they have not. No matter how good our theories are, there is always the possibility that they will be shown to be incomplete, or even downright wrong. Even if a theory has been tested a million times, there may be an exception lurking around the corner. This is why we say that science has an **inductive** component (see Chapter 5 for more on induction). We must assume that our laws will continue into the future, even though we cannot justify this assumption, except by noting that we have little alternative!

It does not follow that we reckon all our theories are wrong – far from it. Scientists have tried very hard to disprove them, in some cases for hundreds of years, and they have failed. The longer a theory has resisted falsification, the more confident we feel about it. That is what Einstein meant when he said: '*Truth is what stands the test of time.*'

Now we know, for example, that:

3 The Earth is not exactly round, but it is actually a bit wider at the equator.

Does that mean that claim **2** was wrong, just like claim **1**? This is an interesting point. It leads to the question, 'How much of today's science is wrong? If it is wrong, why does it work so well?' Perhaps right and wrong are not good ways of describing science; perhaps truth is not what science gives us at all.

What is clear is that a scientific claim is a claim that should lend itself to experiment. We should be able to devise an experiment that could falsify the claim. It is precisely here that we can differentiate between a scientific claim and a non-scientific one.

A Decide whether or not these are scientific claims:

1. The Earth is flat.
2. The Earth is not exactly round, but it is actually a bit wider at the equator.
3. UFOs regularly visit Earth to abduct humans for experimentation.
4. God created the world in seven days approximately 5,000 years ago.
5. God created the Universe.
6. God did not create the Universe.
7. In some remote areas of China, there are people who can jump higher than 10 m.
8. In some remote areas of China, there are people who can jump higher than 10 m, but their society is so secretive that they will never permit outside observers to witness it.
9. Love is more important to human beings than anything else.
10. If you ask people in a multiple-choice question what they find most important, and you include love as a possible answer, then more than 75 per cent will put love at the top of their list.
11. Saying 'I love you' to your partner.
12. Picasso's painting *Cannes, 4a.m.* is a beautiful piece of art.

Discuss these with others to see if you can agree.

Remember that to say that a claim is not scientific does not mean that it is not important. Some of the claims above provide evidence of that – clearly arts, religion and emotion are some of the most important ways of giving meaning to people's lives. The point is that a claim can only be called scientific if it lends itself to scrutiny and rigorous testing. This is a very difficult requirement, but it is precisely the strict adherence to this principle that accounts for the enormous and rapid progress made by science.

A If science never proves anything right, why do we trust it so much?

B Think about the science you learn at school. How likely do you think it is that it is wrong or incomplete? What about the science you read about in magazines such as *Nature*, *New Scientist* or *Scientific American*?

Another important aspect of scientific statements is best illustrated by example. Suppose the time is now one second past 9.00a.m. Consider these statements:

- It is 9.00a.m.
- It is between 3.00a.m. and 3.00p.m.

Both are testable by checking a reliable watch, and so both are scientific claims. The latter statement is, in fact, true, but very unlikely to be useful, whereas the former is false but probably accurate enough for almost any purpose. This clearly shows that there is more to a scientific statement than the requirement that it can be tested. There is also the issue of how much information a statement contains. A highly informative but incorrect theory (the former) is better than a vague but less informative theory (the latter). It may seem odd that a false statement is of more use than a true one – and this may lead us to question precisely what we mean by 'true' and 'false' in this context – but the answer to that question will have to wait until after we have looked at not just the scientific statements, but the scientists themselves.

Science as a human endeavour

A new scientific truth does not win by convincing its opponents and making them see the light, but rather because its opponents eventually die and a new generation grows up that is familiar with it.

Max Planck

The astronomer Carl Sagan argued that the success of science is similar to the success of democracy – both thrive on transparency and in both science and democracy the most effective road to progress is to give everyone the opportunity to have a look at the data. Everyone has the right to contribute, but only the ideas that deliver the goods carry the day. If your ideas don't stand the test of experiment, they'll be ruthlessly demolished, even if your name is Einstein (the work done by Einstein in the latter half of his life is considered ill-conceived by the majority of physicists). Perhaps this is what distinguishes science from other disciplines – because scientists rely on experiment, they can reject most of the rubbish! It does not accumulate and get in the way of new, better ideas.

The idea of testing theories, and the value placed on scepticism, are central to science. Attempts to prove Einstein, Newton, Darwin and all the other great (and not so great) scientists wrong are a central part of the scientific endeavour. After all, is there a better way to convince someone that a theory is valid than to try, but fail, to prove it wrong?

There is an important difference here between science and some other systems that claim to explain something about the Universe. The institutions of science have built-in sceptics – the scientists themselves! It is the sceptics who refuse to accept the current theory, who come up with their own ideas and persuade others that they are right, who win fame, fortune and success. We might usefully contrast this with other areas where scepticism is sometimes regarded as suspicious, and to be avoided.

Sagan goes on to ask:

How is it possible that so many people distrust science, but are willing to put their trust in horoscopes and fortune tellers?

Science tells you: here's what we've got. If you don't agree, show us where we're wrong, and we'll not only accept it, but cherish you as the bringer of new insights. Compare this to the leaders of the local cult or your local astrologist, who tell you:

I cannot explain it to you in ways that you can test and unambiguously confirm, but I have the truth. Trust me and believe me; the truth has been revealed to me.

Why is it that so many people prefer to trust one person who makes non-accountability his trademark rather than trust a community that has made self-criticism and scepticism its main virtue? Perhaps the answer to this is that we have so far been talking about science as it should be practised ideally. Of course, science is carried out by humans, and that means that it should also be studied as a human endeavour, with all that entails.

Perhaps the most interesting aspect of science as a human endeavour has been explored by Thomas Kuhn, a scientist himself, and also an historian and philosopher of science. Kuhn argued that, contrary to what we have said so far, scientists do not work by falsification. Arguing not just on philosophical grounds, but as a matter of historical fact, he suggested that scientists hold some fundamental beliefs (paradigms) so strongly that they are sometimes not prepared to allow them to be falsified; they may ignore or disbelieve findings which seem to disprove them.

Kuhn's classic example is the paradigm of the Earth at the centre of the Universe with the planets and the Sun orbiting in circles. This paradigm was technically falsified by Galileo and Kepler. According to a strictly rational scientific process, we might expect their findings to have been greeted enthusiastically, but it took a long time for their findings to be accepted. Another example is the theory of continental drift (which states that the continents 'slide around' on the surface of the Earth), which was laughed at by the geological community for years before finally being accepted.

The key point here is that it is very difficult to know how to interpret experimental results. When you find a result that seems to indicate that a widely held theory is false, what do you do? Of course, you assume that it is your mistake – and you check the evidence carefully. Even if you can't find the error, which of the possible explanations is more likely:

(a) that you have failed to spot the error
(b) that the famous theory is wrong?

Well, that depends on many things. Once there is enough evidence, the scientific community will accept that a theory has been falsified. But what is enough evidence? That is a question which cannot be answered by science – it is a value judgement that individuals make according to their own personalities and idiosyncracies. There are emotional reasons, too (perhaps some scientific advances are felt to be threatening), and the feelings of the scientific community are of paramount importance. Kuhn stresses, for the first time, the social nature of science.

Consider another example: in 1926, after 25 years of skilful and patient work by physicist D. C. Miller, in which many thousand repetitions of the Michelson–Morley experiment (to measure the speed of light) produced results clearly inconsistent with Einstein's theory of relativity, Miller addressed the American Physical Society, explaining his results. At face value, Miller falsified relativity, but was the theory abandoned or even brought into serious question by the community? It was not. In fact, his results evoked nothing but expressions of regret that such a fine experimental physicist should waste his professional career generating data in which no one was interested. What seems to have been at stake was the professional skill of the scientist rather than the hypothesis he thought he was testing! So the claim that 'experiment is always the final arbiter of a theory' needs some qualification. The philosopher Michael Polanyi writes:

It is the normal practice of scientists to ignore evidence which appears incompatible with the accepted system of scientific knowledge, in the hope that it will eventually prove false or irrelevant.

Many scientists have echoed this. Erasmus Darwin, brother of Charles, said, *'If the facts won't fit in, why so much the worse for the facts.'* Paul Dirac, Nobel Prize-winning physicist, said, *'It is more important to have beauty in one's equations than to have them fit the experiment.'*

Crucially, this view deposes science from its objective, value-free status. After Kuhn we tend to see science as very much a human activity, flawed and multifaceted. And once you start adding competition, fame, fortune and Nobel prizes to the mix then it's no surprise to find that interpretation of evidence can be guided as much by emotion as by reason. The sheer nastiness of scientific feuds takes many by surprise. Matt Ridley writes:

William Cookson, an Oxford geneticist, has described how his rivals reacted to his discovery of a link between asthma-susceptibility and a marker on chromosome 11. Some were congratulatory. Others rushed into print contradicting him, usually with flawed or small sample sizes. One wrote haughty editorials in medical journals mocking his 'logical disjunctions' and 'Oxfordshire genes'. One or two turned vitriolic in their public criticism and one anonymously accused him of fraud.

This is a far cry from the popular stereotype of the objective and disinterested scientists, but perhaps to expect a perfect truth-seeking mechanism from flesh-and-blood people is to expect a bit much.

Let us not, however, get too carried away. The natural sciences have made many magnificent and unprecedented achievements, and we should not pretend that they are completely irrational. Although science is a human activity performed by a human community, it seems to work most of the time. This is truer now than at any time in the past. Today, the greatest dream of many scientists is to prove a theory wrong, since that is how progress is made and fame is won! While conservatism was part and parcel of science a few centuries ago, many scientists would say that things have moved on and that today 'difficult' experimental data would not be ignored. Early last century, it took Einstein less than fifteen years to win the world over to his radically new ideas. Likewise, when Feynman proved previous theories wrong and proposed new ones, they were accepted within a few years. Conversely, when 'cold fusion' was proposed a few years back, experimenters all over the world immediately took up the challenge (of course, the billions of dollars that were available to the finders of cold fusion may have had something to do with it, too). After a tumultuous few months of conflicting results, the scientific community came to the consensus that the phenomenon of 'cold fusion' was simply an error or a hoax: the crucial results could not be duplicated. 'Cold fusion' did not pass the stringent test of experiment.

To overturn a theory now requires less time than it ever did before. But let us not forget that scientists are humans.

A If you did an experiment that seemed to have falsified the law of conservation of energy, what would you do?
B What does this imply for the roles of experiment and falsification in the progress of science?
C If what Kuhn says is true, is this a positive or negative description of science? What might it mean for the commonly-held notion of the methods of science as yielding facts and truths?
D Do you think that Kuhn's model is an accurate description of science?

Science – a universal tool?

Science is nothing but trained and organised common sense.

T. H. Huxley

As we've seen, the method of science is widely applicable, but we haven't made clear what distinguishes the **natural** sciences from other sciences. Natural scientists have a far easier job than **social** scientists (such as economists or social psychologists) because their claims can be defined very precisely. For example, compare a physicist with an economist who has great difficulty in even obtaining precise definitions (what does 'the economy will react adversely to the imposition of currency controls' really mean, in absolutely accurate terms?). This is not economists' fault. Their subject is plagued by many variables that cannot be independently controlled by experiment, and the environment they are trying to describe is continually changing (for example, a society with widespread internet access may react differently to one without). This is in stark contrast to chemists, who keep working and combining the same 100-odd atoms. If nature had decided to work the way economics works, it would introduce a few new atoms every year! The amazing thing about nature is that, as far as we can tell, its underlying laws are **unchanging**. It goes without saying that it is far easier to work in a fixed environment than in an everchanging one. This is the luck of natural scientists, and is another reason for the rapid progress in their fields.

The fact that the natural sciences study an environment that is believed to have fixed laws marks another distinction: it allows researchers in these fields to keep on digging for the underlying

foundations and thereby reduce their theories to fewer and more basic terms. To make progress in the natural sciences means to make things simpler – for example, phenomena like wind, sound and heat, what keeps a solid together, and the principles of cooling and pressure are all manifestations of the same underlying truth, that the world is made up of molecules. Going one step deeper, one asks what molecules are made of, and so on. But progress in economics, for example, has led to greater complexity and an increasing list of exceptions to general rules.

The fact that the laws of the natural sciences are undergoing continuous reduction is also the reason why we have so far restricted our discussion of the natural sciences to physics. The basic laws of chemistry, for example, can be understood with physics (with quantum mechanics, to be precise). The laws of biology are essentially chemical in nature, so arguably they also reduce to physics ultimately. Geology is another discipline in which the underlying principles are physical in nature. In short, the deepest underlying rules of all natural sciences ultimately reduce to physics. However, please remember Feynman's words at the beginning of this chapter. We're not saying that by knowing everything about physics we will also know everything about biology. After all, knowing the rules of chess does not mean you know how to play! There is a distinction between reductionism and elimination – when a subject is reduced to physics is does not necessarily mean that we have found out everything about that subject.

A 'People fall in love because of their psychological make-up. Psychology reduces to biology; biology to anatomy; anatomy to chemistry; chemistry to physics. So to be the best psychologist you can be, you should study physics.' On what grounds would you accept or reject this statement?

B Read the final pargraph above carefully and imagine that at some future date we eventually find all the laws of nature – 'the rules of the game'. What would that mean for our ability to make things and control the world?

C We have considered at least four aspects of sciences – inductivism, falsification, paradigms and creativity. Think of some examples of each aspect. What are the respective roles of each component? Are any components more important than others? What are the problems with each aspect?

D Some sciences are increasingly taking a **holistic** approach whereby they try to avoid **reduction**. Does this mean that they are still sciences, or have they become something else?

E Think back over your science educaton. What did you learn about the way science works?

F Are the theories in this chapter realistic about the way sciences work?

G Are they the way sciences *should* work?

H Ask any scientists you know what they think makes the natural sciences so special.

'Right', 'wrong' and scientific 'truth'

Even if by chance he were to utter the final truth, he would himself not know it: For all is but a woven web of guesses.

Xenophanes

One of the greatest triumphs of the natural sciences is Einstein's theory of general relativity. Combining spectacular creativity, brilliant reasoning, bold conjectures and dramatic experimental confirmation, it seems to be all that science should be.

But what if Einstein was wrong? The history of science is full of theories that once seemed 'right', but which we now know are 'wrong'. Famously, the Earth is not flat, atoms are not the smallest particles, and Mars has no canals on it. Some of today's science seems so outrageous (chaos theory tells us that a butterfly flapping its wings can cause a hurricane on the other side of the world!) that surely it is just a matter of time before today's beliefs are superseded and discarded. So why shouldn't Einstein be wrong?

Well, most scientists believe that eventually Einstein will be proven 'not right'. But 'not right' does not mean 'wrong'. This can lead to confusion because we tend to think of science as black and white. We can argue about shades of grey in the arts, or perhaps the social sciences, but we tend to think of 'truth' and 'certainty' in physics. However, this may be incorrect. Dividing the scientists into the 'bad guys' (who tried hard, but got it wrong) and the 'good guys' (who got it right) is a little too simple.

Of course, Einstein is the archetypal 'good guy'. He managed to solve problems that even the great Newton got wrong. Strange, then, that Newton's 'wrong' ideas are still used by NASA for satellites and space shuttles. Why do all our daily experiences (apples falling and the like) obey his rules? Why does the moon still orbit according to Newton's formulas? Newton's laws work. How can they be wrong?

A If Newton's ideas were wrong, why are they still used? Can wrong theories make correct predictions?

B What are the meanings of 'wrong' and 'correct' in the previous question?

The answer to the apparent contradiction between Newton and Einstein is surprisingly simple. Einstein generally *agrees* with Newton; in fact, the only point of disagreement is over issues that Newton never considered (such as speeds extremely close to the speed of light, or near objects with intense gravitational fields). That is, Einstein built on Newton's theories, added to them and took them to new levels of complexity and sophistication. If Newton had been completely wrong, Einstein could not have been right. To say that Einstein 'disproved' Newton is to miss the point of the process – without Newton, there could not have been Einstein.

'Right' and 'wrong' therefore may not be useful ways to describe scientific theories. Physicist David Bohm puts it well:

The notion of absolute truth is shown to be in poor correspondence with the actual development of science. Scientific truths are better regarded as relationships holding in some limited domain.

New ideas rarely mean abandoning old ideas completely. Rather they stretch, expand and build upon old ideas. Scientists used to argue about whether light was a wave or a particle. It turns out (so we now think) that it is both. The new theory of light does not disprove either old one, rather it unites and enlarges them.

This simple point is often lost in the very human desire to categorise ideas as 'right' or 'wrong'. We like clarity and easy answers and we tend to shy away from more complex notions if we can. This means that we sometimes see a 'scientific revolution' when there was really a slow evolution of scientific theory. Physicist Hendrik Casimir writes:

The gradual evolution of new theories will be regarded as revolutions by those who, believing in the unrestricted validity of a physical theory, make it the backbone of a whole philosophy.

'Right' ideas are ideas that lead to other ideas and that seem to make deep and unexpected connections to other areas of knowledge. Sometimes they lead to a new explanation of a familiar phenomenon. 'Wrong' ideas, by contrast, do not lead anywhere.

By this definition, several 'wrong' ideas are 'right'. We could say that those scientists who once thought that the Earth was flat were 'wrong', but it may be more accurate to say that their theories were limited. If you walk around town, it seems pretty flat. It is all just a matter of perspective (you should be reminded of Newton and Einstein again here). 'The Earth is flat' is 'right' when you are in town. But if you need to travel by aeroplane, then you need to take a larger, wider perspective. You need to expand your theory to take more cases into account. That doesn't mean you were wrong before. It just means that you were only right in some cases.

In other words, 'wrong' means limited. It means that you haven't got the whole story. It doesn't mean that the theory has no value and is useless. We can say that most scientific ideas are 'wrong' as long as we understand what 'wrong' really means. As ever, a thorough understanding of language is essential.

So in all likelihood, Einstein was wrong. He was not able to see all the possible problems or consequences of his theories. He was not omniscient! In fact, anyone who claims to have the absolute truth is probably not in the business of science. 'Right' and 'wrong', in that sense, do not really enter into the scientific process. They are only matters of dogma.

A In your own words explain the difference between 'right' and 'wrong' suggested here. Do you agree?
B According to this way of thinking, what is scientific 'truth'? Is this different to the way we use the word 'truth' in everyday speech?
C Are 'right' and 'wrong' used in the same way in maths, the arts or other disciplines?

Where do we go from here?

As we noted in the introduction to this chapter, it would be foolish to deny that the natural sciences have made, and are still making, astonishing progress in understanding the way the Universe works. They even seem to be telling us something about where we came from and our place in the Universe. But can the sciences ever tell it all? Can they ever tell us something about our daily lives and the human experiences which fill them? Many would say not, arguing that even if we knew every single physical detail about the Universe that it was possible to know, we would not know, for example, what it would be like to be someone else. Nor could any science, no matter how advanced, explain what it feels like to be in pain, or in love, or to taste coffee or wine. The argument seems to have a lot of force – maybe the sciences can never do that for us. Can any other discipline?

To some, the answer is obvious. Where do we regularly seem to 'touch' another human and transcend what has been called our 'egocentric predicament'? The only place, surely, is the arts, and it is to these we now turn.

Further reading

The recent explosion in popular science writing means that you are spoiled for choice in this area, and any good bookshop will have a whole section devoted to the philosophical implications of the natural sciences.

In terms of the scientific method itself, Alan Chalmers' *What Is This Thing Called Science?* (Open University Press, 1979) is an accessible but detailed and lively overview. John Hosper's *An Introduction to Philosophical Analysis* (Prentice Hall, 1957) Chapter 4, also provides a very brief but interesting overview. Karl Popper's *The Logic of Scientific Discovery* (Hutchinson, 1968) and *Conjectures and Refutations* (Routledge and Kegan Paul, 1969) are classics, though a more accessible introduction to his work can be found in the marvellous and very short *Popper* by Bryan Magee (Fontana Modern Masters, 1969). Thomas Kuhn's *The Copernican Revolution* (Random House, 1959) and *The Structure of Scientific Revolutions* (University of Chicago Press, 1970) are also very readable and entertaining. On the issue of science and truth, John Ziman's *Reliable Knowledge* (Cambridge University Press, 1978) is helpful. On the links between science and religion (and interludes into the nature of time, free will, miracles, mind and self) a great starting point is Paul Davies' *God and the New Physics* (Pelican, 1984) or *The Mind of God* (Penguin, 1992). The whole concept of laws of science and their nature is explored in John Barrow's *The World Within the World* (Oxford University Press, 1988). The possible limits of science are discussed lucidly and entertainingly in both John Horgan's *The End of Science* (Abacus, 1996) and John Barrow's *Impossibility* (Vintage, 1999). Carl Sagan's *The Demon Haunted World* (Ballentine Books, 1996) is a classic call for us not to take these limits too far. If you would like to follow up the role of creativity and aesthetics in science then you could try *It Must Be Beautiful: Great Equations of Modern Science* (Granta, 2002), edited by Graham Farmelo.

On science and uncertainty

An essay from *Discover*, by Lewis Thomas.

SCIENCE and technology, hailed just a few years back as the sure solutions for all our increasingly complex societal problems, are both in trouble these days. Part of the difficulty is that the two enterprises, really quite separate, generally seem so tightly linked as to be one thing: the nuclear bomb and energy plants are scientific accomplishments; chemical waste products are the droppings of science; the increased levels of CO_2 in the Earth's atmosphere are pumped there by science; and now we have genetic engineering, computers playing high-class chess, satellites capable of photographing the tears on up-turned faces, overpopulation of the planet by older and older people blocking options for the young. Soon enough we will have to begin worrying about traffic accidents on Mars.

If you concentrate on technology, it can seem as though science has developed into the mightiest force in the affairs of mankind, and is getting out of hand and beyond control because of the overwhelming power of piled-up mountains of new information. There are uncomfortable doubts in the public mind about the risks entailed by learning so much so fast. Soon there will be earnest proposals that science should be slowed down by law to regulate the enterprise more tightly, with agencies deciding in advance that there are some things that human beings are better off not knowing. There is concern that research, left to itself, driven by its implacable reductionism, will quickly penetrate all the great mysteries and we will be left with nothing to contemplate but the nasty little details of a monstrous machine. There is a genuine apprehension that science may be taking the meaning out of life.

But if you concentrate on science, it is in real life not like this at all. We are nowhere near comprehension. The greatest achievements in the science of this and the last century are themselves the sources of more puzzlement than human beings have ever experienced. Indeed, it is likely that these times will be looked back on as the time when science provided the first close glimpse of the profundity of human ignorance. We have not reached solutions; we have only begun to discover how to ask questions.

Science is founded on uncertainty. Each time we learn something new and surprising the astonishment comes with the realisation that we were wrong before. The body of science is not, as is sometimes thought, a huge coherent mass of facts, neatly arranged in sequence, each one attached to the next by a logical string. In truth, whenever we discover a new fact it involves the elimination of old ones. We are always, as it turns out, fundamentally in error.

I cannot think of a single field in biology or medicine in which we can claim genuine understanding, and it seems to me the more we learn about living creatures, especially ourselves, the stranger life becomes. I do not understand modern physics at all, but my colleagues who know a lot about the physics of very small things, like the Universe, seem to be running into one queerness after another, from puzzle to puzzle.

The sense of strangeness and ambiguity is the best evidence that science is working. The world is not a simple place, nor are we simple instruments. We should have known this long ago, but we found it easier in earlier centuries to tell tales to each other, powerfully explanatory but based on pure guesswork, and generally mistaken. Now that we have made a beginning of sorts, it is becoming clear that nothing is clear. I believe that the exploration of nature, given the spectacular human gift of insatiable curiosity, will never be concluded. I cannot for the life of me imagine a time when all our questions will do more than raise new questions, with new astonishments for answers.

It is a risky business, science. Not only do you have to start your work by assuming the existence of wrongness, you must count on a very high probability of being wrong in your own experiments, running into dead ends, finishing the work with that greatest of scientific disasters, a 'trivial' observation. It takes the greatest skill, and a measure of courage, to turn your imagination completely loose and this is the mandatory first step. You make up a story to explain whatever it is that you are curious about and then you design an experiment to test the story, building in all the controls that you can think of in order to make sure that your wish to be right, just this once, will not influence the outcome. This, by the way, is where the greatest danger lies; you can wish too hard for it to be a garden path and overlook the plainest evidence of a blind alley. I do not know of a chancier profession.

It is true that scientists have not done a very good job of explaining what they are up to, but this is not because of any reluctance to display their accomplishments; they tend to brag all over town, to anyone willing to listen. The real trouble is that the public knows too little, and is told by the scientists too little, about the ignorance of science itself.

This has nothing at all to do with the applications of science. The ignorance I have in mind is of another order, unrelated to usefulness, not connected with our capacity as a species to solve practical problems. There are questions of the agenda of modern science that need answering simply for better comprehension, and for the wisdom of a future society.

We know a lot about the structure and function of the cells and fibres of the human brain, but we haven't the ghost of an idea about how this extraordinary organ works to produce awareness; the nature of consciousness is a scientific problem, but still an unapproachable one. We can make good educated guesses about the origin of life on this planet; it must have started, we think, as single-celled creatures resembling today's bacteria, but we have no way of tracking back to the events preceding this first cell, nor can we lay out an orderly scheme for explaining the nearly four billion years of evolutionary process from such a cell to ourselves.

We do not know how the first cells of an embryo, starting from the fusion of an egg and a sperm, sort themselves out with infallible precision into the systems of differentiated cells of a baby, each cell in possession of all the information needed for a complete baby but with most of that information switched off so that it can only become, say, a skin cell or a brain cell. We do not know how normal cells are transformed into cancer cells; we know the names of some of the chemicals, and types of radiation that can launch this process, but the nature of the process itself eludes us.

We know that songbirds have centres on the left sides of the brain for the generation of bird song, and we suspect that this may somehow be related to the lateralisation of speech centres in our own brains, but we do not understand language itself. Indeed, language is so incomprehensible a problem that the language we use for discussing the matter is itself becoming incomprehensible. We do not know what holds us together as a social species; it is a mystery that we are so dependent on each other, in search all our lives for affection, and yet so willing to destroy each other when assembled in larger groups; the failure of nations to conduct their affairs with anything resembling the humanity we expect from each other as individuals is, somehow, a biological problem still beyond our reach. We do not understand the process of dying, nor can we say anything clear, for sure, about what happens to human thought after death.

In short, we are an ignorant species, new to the Earth, still juvenile, still in the earliest stages of inquiry, bound by our very nature to discover more about ourselves and the life around us in which we are, like it or not, embedded. It is in our genes to understand the Universe if we can, to keep trying even if we cannot, and to be enchanted by the act of learning all the way.

But we have a long way to go.